

# **Exploring the Temporal and Spatial Dynamics of UV Attenuation and CDOM in the Surface Ocean using New Algorithms**

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## **LONG-TERM GOALS**

Our long-term objective is to develop a classification for the global ocean based on surface CDOM dynamics that identify regions by variability patterns and the ability to forecast CDOM variations with a known uncertainty.

## **OBJECTIVES**

The central objective of this project is to apply and refine newly developed ocean color algorithms in the examination of the variability and predictability of UV optical properties in the ocean. This includes the following supporting activities: (1) gather, correlate, and provide QA/QC for existing long-term satellite and *in situ* data for use in evaluation of CDOM optics on a global scale (absorbance and UV attenuation spectra), (2) quantify and categorize the variability of global oceanic CDOM parameters (high or low, seasonal or random, existence of long-term trends) (3) provide statistical confidence for models forecasting CDOM optics, (4) examine distinct oceanic regimes for the fundamental causality for CDOM variability.

## **APPROACH**

Previous ONR funding in our lab produced two improved and ready-to-use algorithms (SeaUV and SeaUV<sub>C</sub>; see Fichot (2004), Fichot et al. (2007), and 2004 & 2005 ONR reports for details) for monitoring  $K_d(320-490)$  and  $a_g(320)$  from measurements of spectrally resolved remote sensing reflectance,  $R_{rs}(\lambda)$ . Our general approach for this project is to continue to refine these new models to systematically investigate UV attenuation and CDOM dynamics in specific hydrological and biogeochemical domains in the global ocean.

Using 10-years of SeaWiFS data (1997-2007), we construct an ocean color data set to examine the variability and predictability of UV-Vis attenuation and CDOM dynamics as follows:

First we identify and define CDOM variability patterns in the world's oceans. A time-series analysis is carried out to identify areas with specific CDOM variability and corresponding degrees of predictability that can be quantified. We also examine the seasonal and yearly variability in CDOM in the entire world's ocean for any historical trends occurring over the past decade (1996-2006).

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The second step is to attempt a characterization of the dominant processes that drive variability of UV attenuation and CDOM in the surface ocean. Although absolute quantification of the relative magnitude of each process may be beyond the scope of the current plan, it is feasible to define regions of the ocean where certain processes dominate our observations.

For this, we look at the cross-correlation for different lag times between CDOM absorbance and the incident irradiance (obtained from the System for the Transmission of Atmospheric Radiation (STAR) model) together with relative photobleaching rates. Ocean color derived chlorophyll concentrations (and/or primary production) as well as global monthly climatological data of the mixed layer depth available from the Naval Research Laboratory Mixed Layer Depth (NMLD) Monthly Climatology (data available @ <http://www7320.nrlssc.navy.mil/nmld/nmld.html>) will also be investigated for their relationship to CDOM variability. For specific coastal areas, riverine discharge and precipitation data will be considered. We will develop a package compatible with the SEADAS tools (IDL, Fortran), to ensure utility for other studies of photochemistry and photobiology. This package will couple the STAR irradiance model and the SeaUV/SeaUV<sub>c</sub> algorithms to produce maps of underwater irradiance,  $E_d(z)$ , from normalized water-leaving radiances, geo-location and ancillary data (ozone, windspeed, etc.).

## WORK COMPLETED

- We completed validation of SeaUV/SeaUV<sub>c</sub> using in situ data and published the models and algorithms in Remote Sensing of the Environment.
- We compiled and included the 10th year of global CDOM and SeaWiFS data for correlation and match-up analysis.
- We used the SeaUV/SeaUV<sub>c</sub> model to update UV optical properties and CDOM absorbance, ( $a_g$ ) estimates to cover 10 years of remotely sensed VIS data and updated variability trends.
- We constructed a preliminary classification for CDOM variability in the global ocean.
- We obtained new optical data from Sapelo Island to begin evaluation of the SeaUV/SeaUV<sub>c</sub> model in dark coastal waters.
- We developed new algorithms to account for the effects of clouds on UV-Vis partition between direct and skylight for a more accurate calculation of *in situ* scalar irradiance.
- Developed a CO photoproduction climatology and submitted manuscript to GBC.

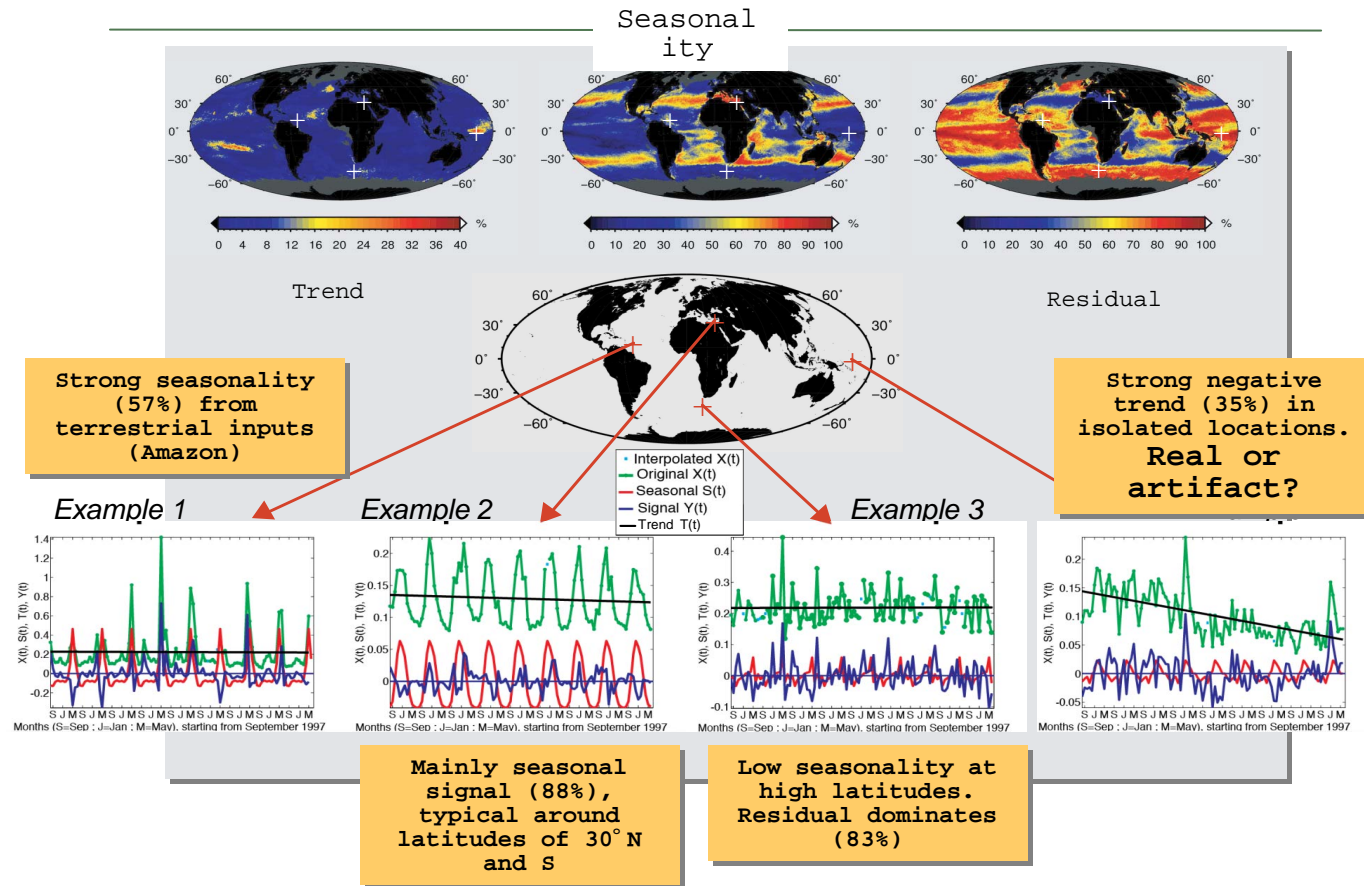
## RESULTS

SeaUV was applied to SeaWiFS monthly-binned normalized water-leaving radiances in order to retrieve  $a_g(320)$  estimates. The resulting time series data for  $a_g(320, t)$ , where  $t$  is a month of a year, were processed to remove outliers ( $|a_g(320, t)| > \mu + 3\sigma$ ) where  $\mu$  is the mean and  $\sigma$  the standard deviation. Time series of the absorption coefficient of CDOM at 320nm were thus obtained at global scales (500 pixels from 90°N to 90°S and 1000 pixels from 180°W to 180°E) for 10 years from

September 1997 through September 2007. Most time series data sets had missing values. To account for missing values in the data set, we arbitrarily chose 70% as the maximum number of values necessary to conduct a proper time series analysis. Consequently, no time series analysis was conducted where less than 70% of the time series was represented. Missing time point values were estimated through linear interpolation between available data where required.

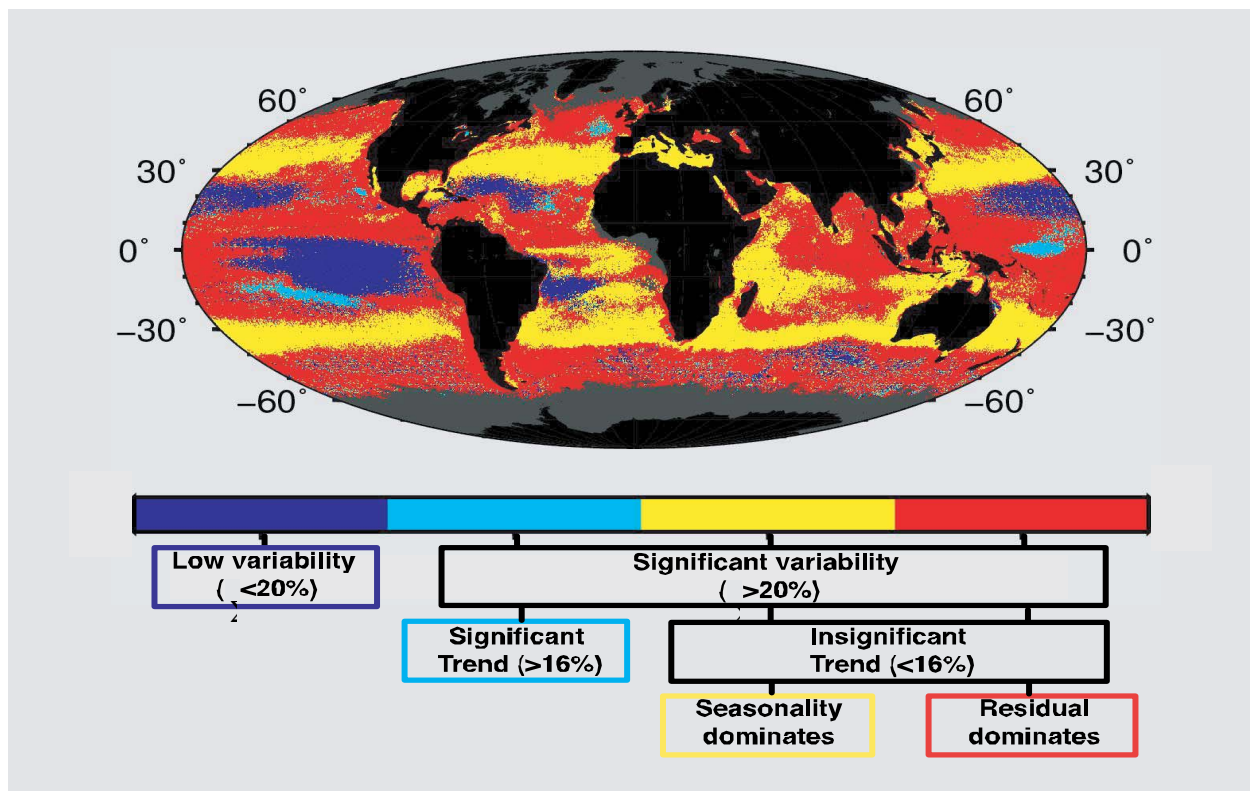
The decomposition of the time series into several components was done using a "classic" technique known as the *Census I* method which breaks down the series into a trend, a seasonal signal, and a residual (or noise) component. Assuming an additive model (rather than multiplicative), the original time series,  $X(t)$ , can thus be decomposed using the following equation:  $X(t) = T(t) + S(t) + Y(t)$  where  $T(t)$  is the trend,  $S(t)$  is the seasonal component and  $Y(t)$  is the residual signal which is stationary and has a mean of zero. Details of this method are contained in our 2006 ONR annual report.

Figure 1 is a composite figure showing the time series analysis results using  $a_g(320, t)$  as an example (representing CDOM). Four example locations were chosen in order to illustrate the differences in the relative contributions of  $T(t)$ ,  $S(t)$  and  $Y(t)$  to the total variability of  $X(t)$  in specific oceanic locations. In all examples, the original time series (green line) can be reconstructed if the trend (black line), the seasonal component (red curve) and the residual signal (blue curve) are added to each other.



**Figure 1. Global distribution of variance  $X(t)$  into seasonal ( $S(t)$ ), trend ( $T(t)$ ) and remaining ( $Y(t)$ ) components with examples [upper panel: three global maps of variance showing rainbow scale (0%=blue, 100%=red) trend, seasonal, and residual variance. The middle image shows global position of oceanic examples for closer analysis in lower panel. From left to right, the four lower panels show the ten year trend variance for  $a_g(320)$  (y-axis =magnitude of variance, x-axis=month) in the Amazon outflow (57% seasonal,), in the Mediterranean(88% seasonal typical of 30-degrees N and S latitude), just south of the Cape of Good Hope, RSA (83% residual), and in the southwest Pacific (strong negative trend 35%)]**

Figure 2 depicts a global map with classifications based on the dominant source of CDOM variability as obtained from our time series analysis (Figure 1). The first division is between those areas that are not variable with regard to CDOM ( $< 20\%$  variation over the 10-years data set) and those that are. Areas with  $> 20\%$  CDOM variability are further divided into those with significant trends ( $> 16\%$  of the variability) and those with little or no trend ( $< 16\%$  of the variability). Of the remaining areas, the classification splits them into area where either seasonality or the residual dominates the variability.

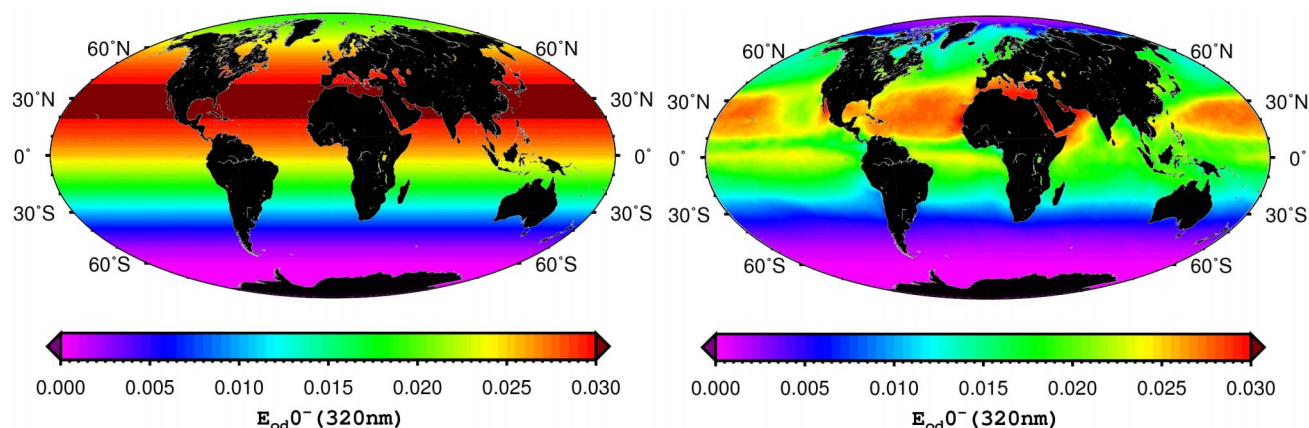


**Figure 2. Global classification of CDOM variance based on 10-year SeaWiFS data for which we calculated  $a_g(320)$  with the SeaUV algorithms. [A global ocean map with classifications depicted using dark blue, light blue, yellow, and red to represent areas where CDOM exhibits low variability, variability exhibits a significant trend, variability is dominated by seasonality and residual respectively. Yellow bands occur between 30 & 40 degrees N and S latitudes. Light blue patches occur northwest of Spain, in the south Pacific around the equator in the west and in a streak around 20 degrees S in the central S. Pacific. Dark blue is a large patch in the S. Pacific from 0 to 20 degrees S just above the trend area. Red is spread through all other area and dominates high latitudes.]**

These classifications do not necessarily reflect quantitative predictability. For instance, some seasonally dominated areas allow timing of CDOM variations to be predicted but not their magnitude (Figure 1, Example 1) while others allow prediction of both (Figure 1, Example 2). Further examination of these differences in CDOM variability may allow evaluation of the processes underlying their patterns. The unexpected CDOM trends in the open ocean identified by this project are especially interesting and await a full analysis.

Because the dominant loss term for CDOM in the ocean is photochemical fading (or photobleaching), and since all of the areas identified to have a significant trend are *negative* in direction, we have put a good deal of effort into developing climatology for accurate UV light fields in the surface ocean. While SeaUV does an admirable job of estimating UV attenuation once photons are in the ocean, the correction for clouds (which spectrally alters both the magnitude and geometry of UV radiation arriving at the air-sea interface) in irradiance models has been challenging to quantify.

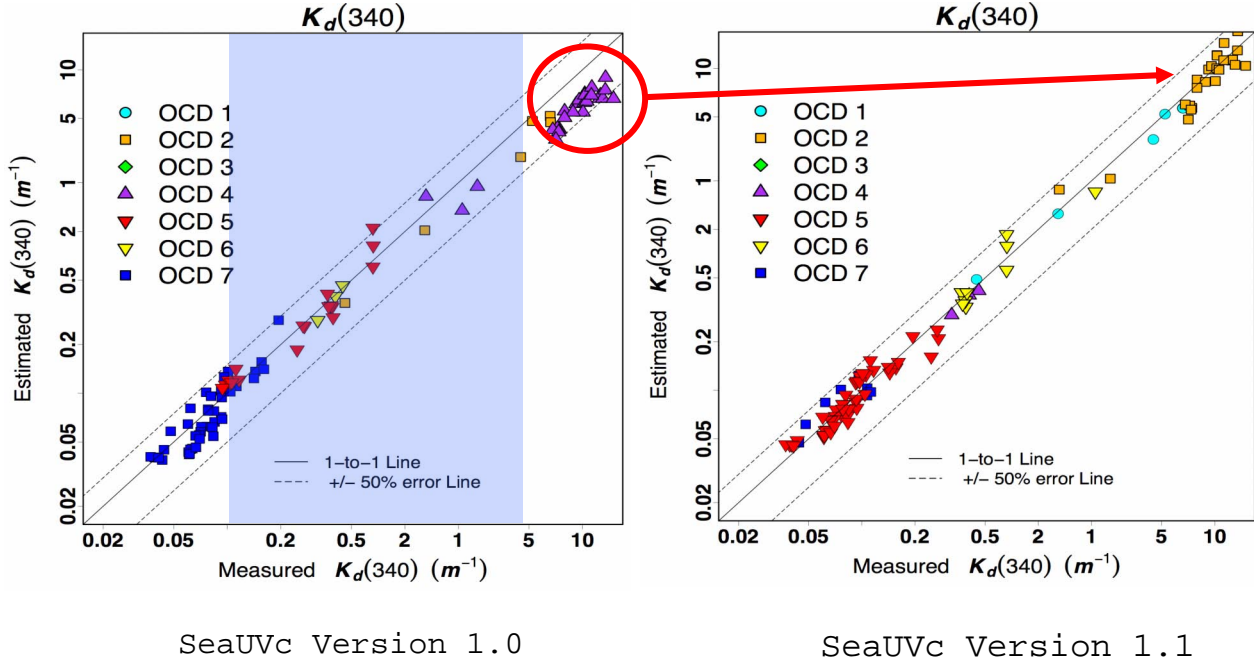
We have developed algorithms that take the clear sky solar irradiance output from the STAR model, uses TOMS data and UV reflectance to develop a cloud-cover climatology for the same 10-year period for our time series, and, using relationships developed by Grant and Gao (2003), calculates the direct-to-sky ratio for solar radiation incident on the ocean surface. This is done as a function of wavelength, time of day, latitude, and percent cloud cover in every pixel. With better irradiance geometry, spectral reflectance that depends on incident angles is better defined and allows a much more accurate calculation of spectral scalar irradiance just below the ocean's surface and development of a depth-resolved global climatology for UV in the ocean. Figure 3 shows a comparison of the 10-year global climatology for the month of June between clear-sky irradiance and cloud-corrected scalar irradiance just below the sea surface at 320 nm ( $E_{\text{od}}^0(320\text{nm})$ ). In our evaluation of CDOM variability, if UV is driving negative CDOM trends, these new, more regionally accurate UV maps together with SeaUV attenuation estimates should provide revealing correlations.



**Figure 3. Comparison of clear-sky and cloud-corrected global scalar irradiance just below the sea surface, 10-year climatology for the month of June for data generated with the STAR solar irradiance model. [two global maps with rainbow coloration from purple=0 to red=0.03. Strong latitudinal zones are evident in the clear-sky data panel (left) reflecting solar elevation, dark red band at 30 degrees N. The cloud-corrected data panel (right) shows both less total irradiance (for example, orange pixels at 30 degrees N) and broken patterns (for example, blue at 5 degrees N and purple in the Arctic) due to cloud cover and altered reflectivity due to resultant sky:direct changes.]**

Another result from this project has been related to our continual evaluation of the performance of the SeaUV algorithms in diverse oceanic systems. We have collected (both by mining existing optical data sets and using our own data from recent “cruises of opportunity”) a limited amount of new optical data from the clearest oligotrophic waters in the South Pacific (courtesy of Marc Tedetti) to the dark coastal waters on the coast of Georgia at Sapelo Island (our data). We implemented the current

SeaUVc model to these new data and examined the resulting estimations for UV attenuation and CDOM absorption coefficients. We then incorporated the new data into the training data set and “re-trained” the PCA components. Figure 4 shows the results of this exercise using attenuation at 340 nm as an example. The data outside our original training data set (original training range is represented by the blue box, Figure 4, left panel) was not well defined with the original SeaUVc algorithms, particularly our dark coastal samples. Once the model was retrained with the new data (Figure 4, right panel) the fit was significantly improved. This continual retraining of the SeaUV models will continue as new data is obtained. In it’s current configuration, the more high-quality data that we can obtain from diverse optical situations, the better SeaUV should perform for evaluation of CDOM dynamics, particularly in the difficult optical situations found in the coastal ocean.



**Figure 4.** Comparison of the SeaUVc model before (left panel) and after (right panel) retraining with data having UV optical properties outside the original training data set. [two panels, both with x-axis = measured attenuation at 340 nm ( $K_d(340)$ ), y-axis = model estimates for attenuation at 340 nm. Both show good correlation with almost all points inside the 50% error line. The left panel, before re-training SeaUVc, shows marked overestimation of dark samples ( $K_d(340) > 5$ ) while the re-trained model (right panel) shows very good agreement between model estimates and measured values for  $K_d(340)$ .]

## IMPACT / APPLICATIONS

The SeaUV/SeaUV<sub>c</sub> model has proved to significantly improve our ability to estimate UV optical properties and CDOM dynamics in the ocean and is applicable to all marine environments including both optically shallow and deep situations, areas of high productivity and particle loads, open ocean, coastal and estuarine waters. Understanding of the variability in CDOM will produce better models for photochemical distributions. Better quantification of CDOM will allow better corrections for CDOM in chlorophyll algorithms and characterization of the UV light field in the ocean. Our new algorithms

to account for cloud affects on modeling UV scalar irradiance in the ocean with prove useful to all fields studying the biogeochemical role of UV in the ocean. Once other climatologies (mixed layer depth, wind mixing, temperature variations, circulation mapping, etc.) can be effectively combined with the CDOM optical models, reliable predictive models that calculate UV and blue spectral inherent optical properties will be possible.

## **RELATED PROJECTS**

This ONR project to refine and apply SeaUV/SeaUVC to the evaluation of UV optics and CDOM dynamics in the global ocean will benefit from collaboration with a newly funded NASA project (Miller, PI) to use these same models to examine photochemical carbon cycling in the south Atlantic bight off the coast of the S.E. United States.

## **REFERENCES**

Grant, R.H., and W. Gao (2003) Diffuse fraction of UV radiation under partly cloudy skies as defined by the Automated Surface Observation System (ASOS). Journal Of Geophysical Research, Vol. 108, No. D2, 4046, doi:10.1029/2002JD002201.

## **PUBLICATIONS**

Fichot C. G., S. Sathyendranath, and W. L. Miller (2007) SeaUV and SeaUVC: Algorithms for the retrieval of UV/Visible diffuse attenuation coefficients from ocean color. (in press) Remote Sensing of the Environment.

Fichot C. G., and W. L. Miller (2007) Monthly climatology of oceanic depth-resolved carbon monoxide photoproduction estimated by remote sensing. (submitted) Global Biogeochemical Cycles.